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ABSTRACT

Experiments and simulations are performed to study flow behavior in biomass gasification reactor. Glass beads of particle size 350 µm and density 2500 kg/m^3 are used for experiments and simulations. A validated CFD model is established. Using the same CFD model, simulation is performed for quartz sand of particle size 500 µm fluidized with high temperature steam which is used as bed material in the gasification reactor.

INTRODUCTION

Bubbling fluidized bed is widely used in industrial processes. It has gained increasing application due to good mixing, heat and mass transfer. Biomass gasification reactor for combined heat and power (CHP) production is one of them.

Flow behavior and fluidization properties in the gasifier are studied by considering the operating parameters such as pressure drop, minimum fluidization velocity and bubble behavior. These parameters significantly affect the efficiency of the gasifier. It is essential to study the flow behavior in the reactor in order to choose correct parameters for a given flow regime. Experimental study of the parameters in a plant operating at high temperature is difficult.

Down-scaled models are used to simplify the task. In the gasifiers, high temperature steam is used as a fluidizing gas. In the down-scaled model ambient air is used instead of the high temperature steam (1-3).

High temperature steam and ambient air has different density and viscosity. In order to consider these factors with existing scaling laws (4), the cold model requires particles with very high density and very small particle size. This kind of particles is not easily available in the market. Particles used for the experiments in downscaled cold models do not have the physical properties required by the existing downscaling laws. Therefore, computational fluid dynamics (CFD) could be a suitable solution for the study of flow behavior in the biomass gasification reactor. In order to make CFD a suitable tool for the study of flow behavior in fluidized bed gasification reactors, an established model is required. The model is established with validation against the experimental measurements.

Wach em *et al* (5) has compared simulated results for Geldart B particles with experimental data in literature. Taghpour *et al* (6) have compared modeling prediction with experimental measurements. Hamzehi *at al* (7) studied the effect of gas velocity and particle size using CFD model. Azadi (8) has used the CFD model to simulate elutriation of limestone from binary mixture of particles and compared the results with experimental measurements. Sahoo *et al* (9) has studied hydrodynamics of semi-cylindrical gas-solid fluidized bed. Reasonable agreements between computational and experimental results have been reported.

Prior to this work, CFD simulation and experimental work is performed by the authors for glass beads of mean particle size of 500 µm (10). The model prediction has good agreements with experimental measurements.

The bed material in a typical gasification reactor is quartz sand of mean particle size 500 µm and density 2500 kg/m^3 fluidized with high temperature steam (11).Theoretical minimum fluidization velocity (12) calculated for these particles is the same as the minimum fluidization velocity of glass beads of density 2500 kg/m^3 and particle size 350 µm fluidized with ambient air. Therefore, the glass particles of size 350 µm are used in the experiments in order to investigate whether the flow behaviors are similar to steam fluidized quartz sand.

Experiments are performed in a cold model of bubbling fluidized bed. The fluidizing gas is ambient air. Commercial CFD software package ANSYS/ Fluent 12.1 has been used for computational study. The computational and experimental results are in good agreements to each other. A validated CFD model is established for the particles.

Using the same CFD model, further computational study is performed for the 500µm quartz sand fluidized with a high temperature steam.

THEORETICAL CALCULATION

The mean particle size and density of the bed material are 500 µm and 2500 kg/m^3. Fluidizing gas is steam at 800^{0}C. The steam has density and viscosity about 0.29 kg/m^3 and 4.1x10^{-5} Pa·s respectively (2). A theoretical minimum fluidization velocity of the particles is calculated using equation (1) derived from Erguns equation with gravity- equals - drag balance (12). Based on this equation the minimum fluidization velocity is calculated to be 0.12 m/s.

$$u_{mf} = \frac{(\Phi \cdot d_s)^2 (\rho_s - \rho_g) \cdot g}{150 \cdot \mu} \cdot \frac{\varepsilon_{mf}^3}{1 - \varepsilon_{mf}} \qquad (1)$$

The maximum gas velocity in the gasification reactor is $5u_{mf}$. With this velocity, particle Reynolds's number does not exceed the value of 3. According to Glicksman's viscous limit set of dimensionless parameters, only Froude number and the ratio of minimum fluidization velocity to superficial gas velocity are important for this limit [4].

Glass beads of particle size 350 μm fluidized with ambient air give the same theoretical minimum fluidization velocity of 0.12 m/s. The objective of the preliminary theoretical calculation is to study whether the flow behavior of the gasifier fluidized with high temperature steam can be simulated in a cold flow model using 350 μm particles and air at ambient conditions.

EXPERIMENTAL SET-UP

Experiments are performed in a cold cylindrical fluidized bed with height 1.4 m and diameter 0.084 m. The pressure sensors are located along the height of the cylinder and connected to a lab-view program for data storage as shown in Figure 1.

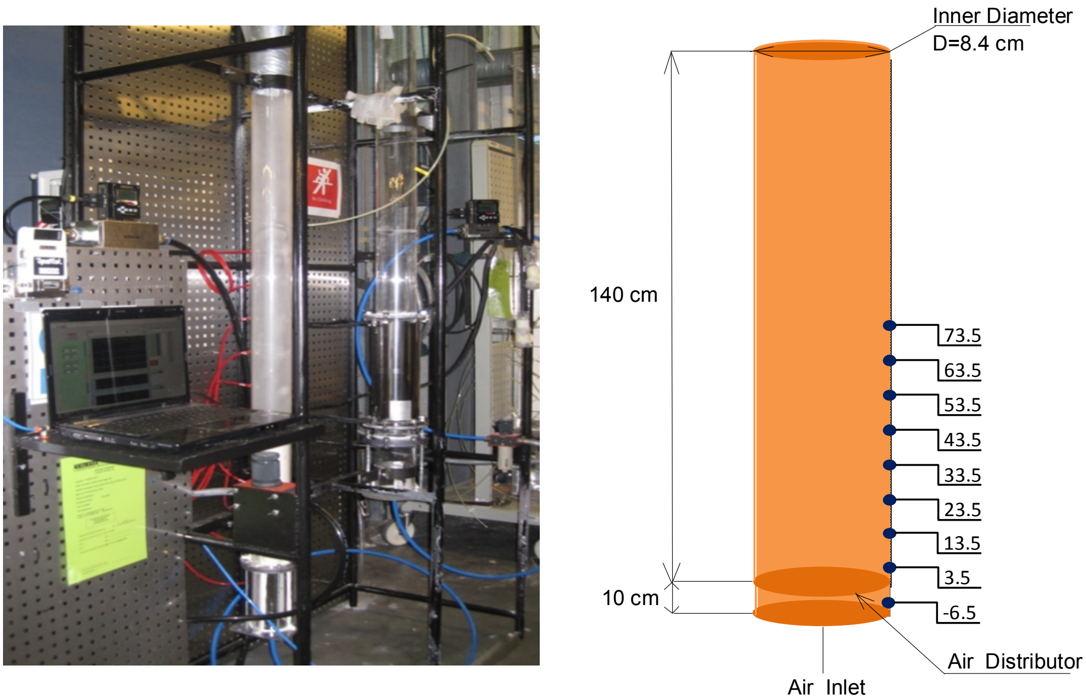

Figure 1: Experimental set-up: fluidized bed with pressure reduction valve, digital flow controller, pressure sensors.

The air flowing through an air distributor is controlled using the lab view program in order to maintain a steady flow of gas. The properties of gas and particles used in the experiments are presented in Table 1.

Table 1: Properties of gas and particles

Parameters	Value	Remarks
Particle density [kg/m^3]	2500	Glass
Gas density [kg/m^3]	1.225	Air
Gas viscosity [pa.s]	1.78x10^{-5}	Air
Particle diameter [μm]	350	Mean

COMPUTATIONAL MODEL

A multiphase Eulerian model describes the gas-solid fluidized bed consisting of two interpenetrating fluids. A non-steady state model is applied in order to consider the transient nature of a gas-solid bubbling fluidized bed system (13). Mass and momentum balance equations are solved for both the solid and gas. The kinetic theory of granular flow has been applied. The theory considers the conservation of solid fluctuation energy. Other constitutive equations for the model are applied in accordance to the models suggest by Jayarathna, S.A.(13). The parameters used in the simulations are presented in Table 3.

Table 3: Simulation parameters

Parameters	Value	Remarks
Particle density [kg/m^3]	2500	Glass
Gas density [kg/m^3]	1.225	Air
Gas density [kg/m^3]	0.29	Steam
Gas viscosity [Ps.s]	1.78x10^{-5}	Air
Gas viscosity [Ps.s]	4.1x10^{-5}	Steam
Particle diameter [µm]	350; 500	Mean
Restitution coefficient	0.9	Specified
Initial solid packing	0.6	
Maximum solid volume fraction [-]	0.63	
Bed diameter [m]	0.084	
Static bed height [m]	0.32	
Time step	1x 10^{-5}	
Number of iterations per time step	40	

In the first case, the simulations are performed with 350 µm particles with air as fluidizing gas. The particles and the gas properties are similar to those used in the experiments. In the second case, the simulations are performed with 500 µm particles and steam as fluidizing gas

RESULTS AND DISCUSSION

A series of experiments are performed for the glass beads of mean particle size 350 µm at ambient conditions. Pressure standard deviations calculated for a series of superficial air velocities are shown in Figure 3. Below minimum fluidization velocity (u_{mf}), the solids are relatively quiescent and the pressure fluctuations in the bed are negligible. The fluctuations are significant as the bed starts fluidizing.

The figure shows significant pressure fluctuations at superficial gas velocity of 0.14 m/s in the experimental measurements and 0.15 m/s in the simulation results. This indicates fluidizing condition of the bed. The experimentally measured u_{mf} is higher than the theoretically calculated value. The deviation between the experimental and theoretical value is 17%. Theoretical calculation involves mono-sized particles, whereas particles with a range of particle sizes are used in the experiments. The u_{mf} is affected by the particle size distribution. Computational pressure standard deviation indicates that the values of u_{mf} for 350 µm glass particles fluidized with air and 500 µm quartz sand fluidized with steam are about the same. The values deviate from experimental measurements by 7%.

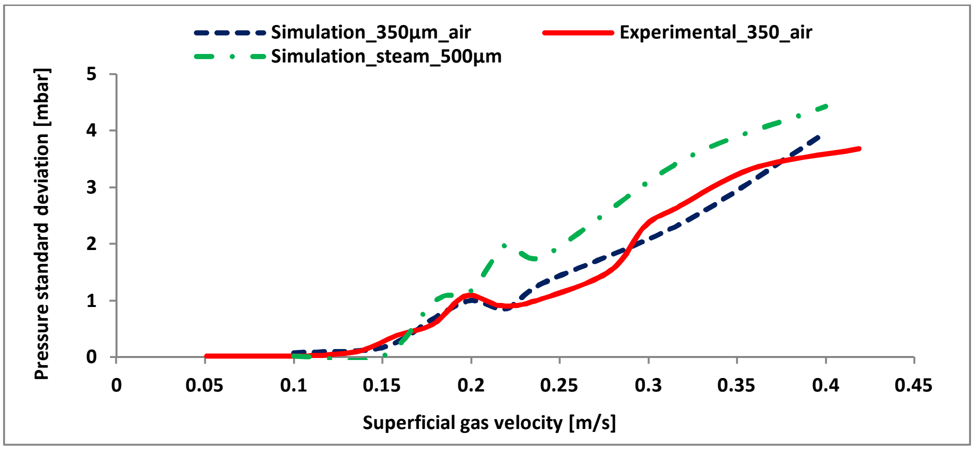

Figure 3: Comparison of pressure standard deviation as a function of superficial air velocity.

The experimental and computational pressure drops after minimum fluidizations agree well as can be seen from Figure 4. Below minimum fluidization the experimental and computational pressure drop seems to deviate significantly. This is because the model in Fluent does not consider the condition of the bed before fluidization.

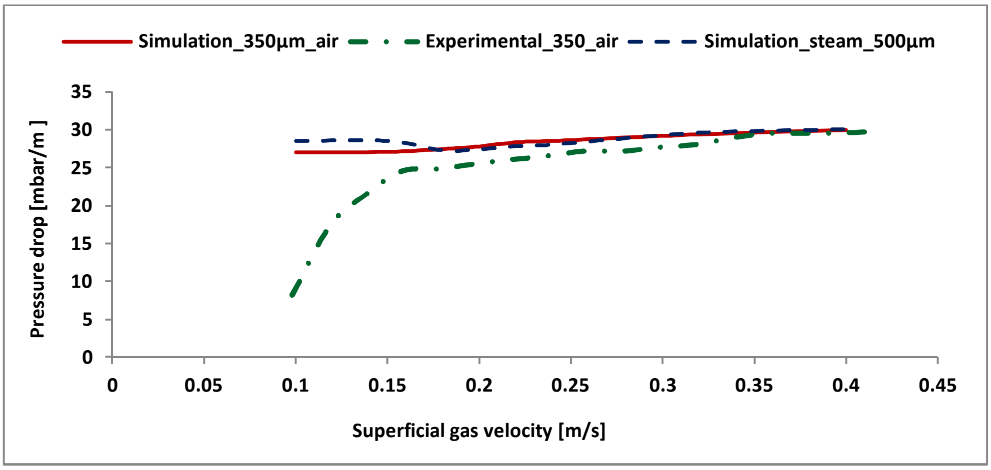

Fig.4. Comparison of experimental and computational pressure drop as a function of superficial air velocity.

Computational results of solid volume fraction fluctuations are used to study the minimum fluidization condition and the bubble behaviors. The solid volume fraction is monitored at different levels of the bed for a series of superficial gas velocities. Before the minimum fluidization condition, fluctuation of solid volume fraction is negligible as the particles do not have significant movements. At the superficial gas velocity of 0.15 m/s, the fluctuation of solid volume fraction is almost negligible for both the steam fluidized and air fluidized particles. This indicates the inception of fluidization condition. At the superficial air velocity of 0.18 m/s, significant fluctuation of the solid volume fraction indicates the bubble formation as shown in Figure 5.

The bubble activities are started at this velocity for the both air fluidized and steam fluidized particles.

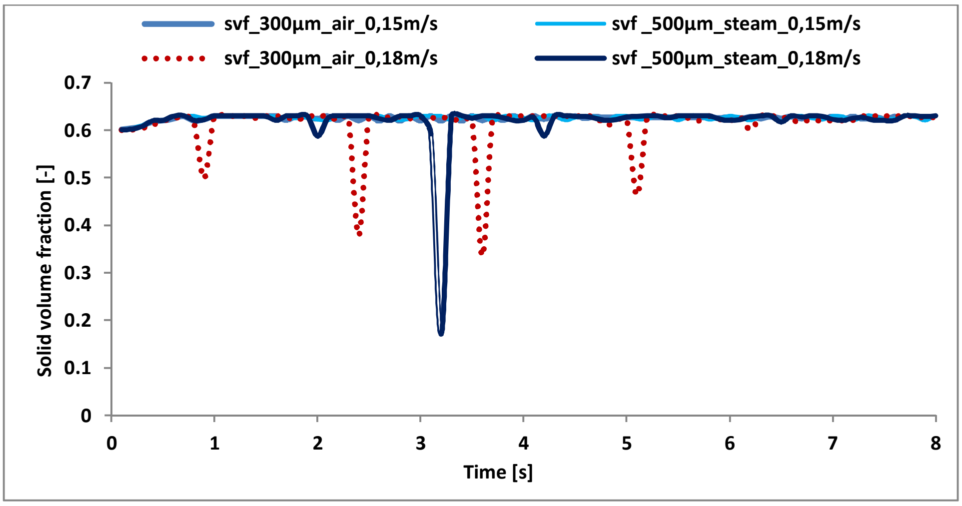

Figure 5. Comparison of simulated solid volume fraction as a function of time. Bed height 0.23m.

At the superficial gas velocity of 0.20 m/s, significant fluctuation of solid volume fraction indicates the increasing bubble frequency with superficial gas velocities as shown in Figure 6.

The figure shows the bubble frequencies for 350 µm particles fluidized with air and 500 µm particles fluidized with steam are 0.25 bubbles per second and 0.38 bubbles per second respectively.

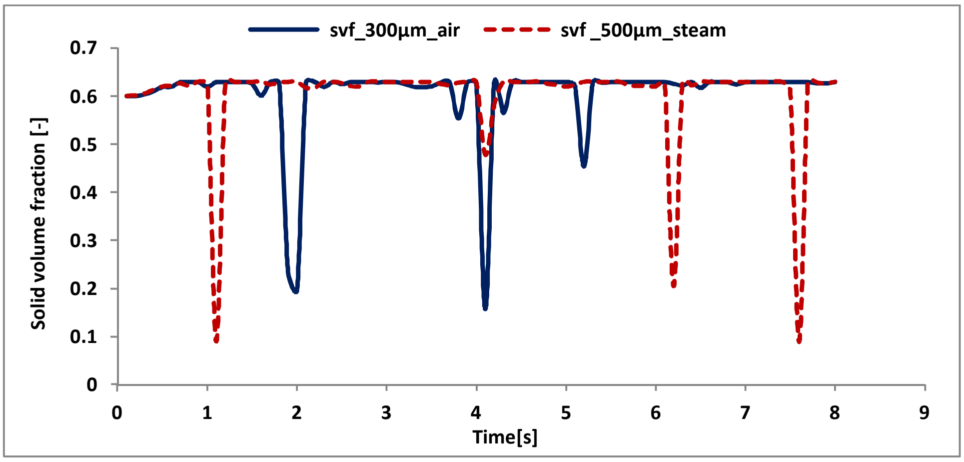

Figure 6: Comparison of solid volume fraction as a function of time.
Bed height 0.23m. Superficial gas velocity 0.20 m/s.

The bubble frequency and bubble size are compared in Figure 7 at the higher gas velocities. The contour of solid volume fraction indicates that the bubble behaviors for air fluidized and steam fluidized particles deviate at higher gas velocities.

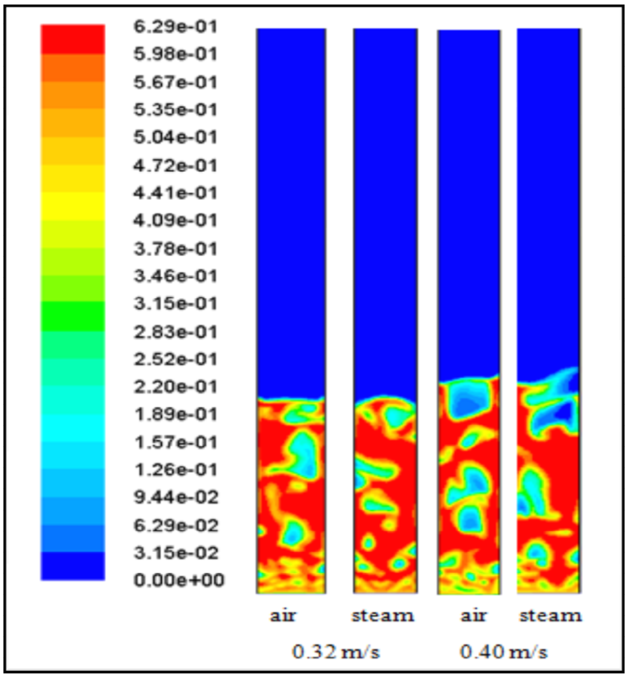

Figure 7: Comparison of contours of solid volume fraction.

CONCLUSION

A multi-phase Eulerian model is applied to predict the flow behaviors and fluidization properties of 500 µm steam fluidized quartz sand and air fluidized 350 µm glass beads. The results are compared. The minimum fluidization velocity is predicted using pressure standard deviation. Predicted u_{mf} for both the particles is the same, 0.15 m/s. Preliminary calculation of theoretical u_{mf} for the particles is 0.12 m/s. The experimental measurement of u_{mf} for air fluidized 350 µm glass beads is 0.14 m/s. The deviation of u_{mf} between experimental measurements and simulated results is 7%. The computational pressure drop across the bed height for 350 µm glass particles fluidized with air and 500 µm quartz sand fluidized with steam are about the same and the results deviate from the experimental measurements by 18% at minimum fluidization condition

Minimum bubbling velocity, bubble size and bubble frequency are studied using the fluctuation of solid volume fraction and the contours of solid volume fraction. Computational minimum bubbling velocity is 0.18 m/s for both quartz sand and glass particle. Bubble size and frequencies deviates for the two cases as the gas velocities increases from minimum fluidization velocity.

SYMBOLS AND ABBREVIATIONS

CFD	computational fluid dynamics
CHP	combined heat and power
d_s	particle diameter [m]
g	acceleration due to gravity [m/s^2]
u_{mf}	minimum fluidization velocity[m/s]
ρ_s	particle density [kg/m^3]
ρ_g	gas density [kg/m^3]

μ gas viscosity [Pa·s]

ϕ particle sphericity [-]

ε_{mf} void fraction at minimum fluidization [-]

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